Interactions in massive binary stars as seen by interferometry

Florentin Millour, Anthony Meilland, Philippe Stee, Olivier Chesneau

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Abstract With the advent of large-collecting-area instruments, the number of objects that can be reached by optical long-baseline interferometry is steadily increasing. We present here a few results on massive binary stars, showing the interest of using this technique for studying the insight of interactions in these systems. Indeed, many massive stars with extended environments host, or are suspected to host, companion stars. These companions could have an important role in shaping the circumstellar environment of the system. These examples provide a view in which binarity could be an ingredient, among many others, for the activity of these stars.

1 Introduction

The most massive stars are still a puzzle, especially regarding their evolution. They are the best candidates to be progenitor of type II supernovas, which are one source of metallic enrichment of the interstellar medium, but they also input kinetic energy to their vicinity, triggering densification and collapse of neighboring interstellar clouds.

In the past years, many new observing techniques have appeared, that allow one to access unprecedented angular resolution. Therefore, the detection and characterization of circumstellar environments (hereafter CSEs) around massive stars has become a reality. A by-product is that several new companion stars have been discovered using high-angular resolution techniques, being adaptive optics, lucky imaging, or long-baseline interferometry.

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We try here to give an insight of the influence of stellar companions to the structure of CSEs by showing a few examples of massive stars, ranging from the classical Be stars up to the most massive blue supergiant stars.

2 Interactions in intermediate-mass stars: classical Be stars

Binarity may play a non-negligible role in the formation of circumstellar disks around classical Be stars. These stars close to main sequence are known to be fast rotators, however the most recent studies (Frémat et al., 2005; Cranmer, 2005; Meilland et al., 2011b) indicate that they are not all critical-rotators, so rotation cannot be the only mechanism involved in the mass-ejection. Recent studies like Moreno et al. (2011) try to investigate the role of the gravitational influence of a companion star in a few extreme cases. However, such influence is not the only physical process proposed as an additional momentum source to cancel the stellar gravity. Radiative pressure (Abbott, 1979), non-radial pulsations (Rivinius et al., 1998), or even magnetism Li et al. (2008) have also been suggested to play such a role.

To progress in the understanding of the physical processes responsible for the Be phenomenon one needs to resolve their CSE both spatially to obtain informations on the distribution of matter surrounding the star, but also spectrally to get access to the kinematics of the ejected matter. Consequently, spectro-interferometry is the most suitable technique to study these objects. First VLTI/AMBER (Petrov et al., 2007) and CHARA/VEGA (Mourard et al., 2009) observations of Be stars have evidenced that the matter is mostly concentrated into the equatorial plane and that this geometrically thin disk is dominated by rotation with a rotational law close to the Keplerian one (Meilland et al., 2007b,a, 2011b; Carciofi et al., 2009; Delaa et al., 2011; Kraus et al., 2011).

An example of spectro-interferometric observations with the VLTI/AMBER well-fitted by a simple geometrically thin rotating disk model is plotted in Fig 1. As seen in this figure, a rotating disk provides typical ”W”-shaped visibilities and ”S”-shaped phases as long as the disk is not fully resolved by the interferometer (top plots), whereas it gives more complex phases shape (double-”S”) when it is fully resolved (bottom plots).

Few interferometric observations also suggest the presence of a non-negligible polar wind (Kervella & Domiciano de Souza, 2006; Meilland et al., 2007b). Moreover, thanks to interferometric measurements of the projected disk flattening, the star inclination angle can be inferred without ambiguities, and consequently, the rotational velocity of the central star can be determined. In the first spectro-interferometric survey of Be star, Meilland et al. (2011b) show that the stars are rotating at 82 ± 0.07% of their critical velocity (V_c), a result compatible with estimation from Frémat et al. (2005, see Fig. 2). Finally, interferometry can also help to discover new companions as evidenced in the case of δ Cen Meilland et al. (2008).

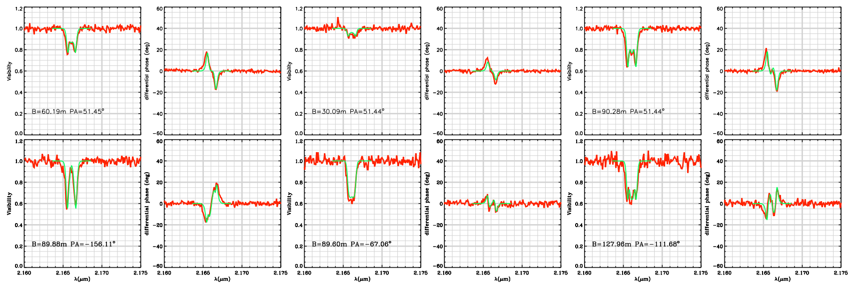

Fig. 1 α Col selected differential visibilities and phases from 2 VLTI/AMBER HR measurements (red line). Each row corresponds to one VLTI/AMBER measurement (3 different baselines). The top row shows short baselines (barely resolved disk) while the bottom row shows long baselines (fully resolved disk). The visibilities and phases of the best-fit geometrically-thin-rotating-disk model is over-plotted in green. From Meilland et al. (2011b).

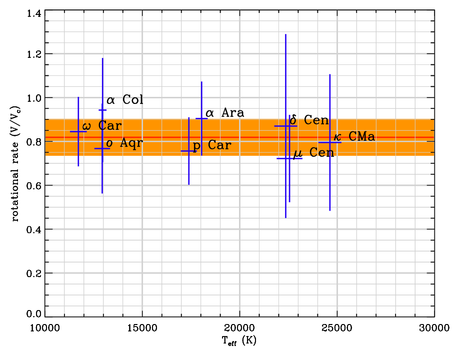

Fig. 2 A set of 8 Be stars observed with long-baseline interferometry, showing for the first time the rotation rate of the central star free of any inclination effect. We show here that the rotation rate is roughly constant whatever the star temperature, at $C \approx 80\%$ of the critical rotation. This points to a different process than rapid rotation for all the stars to expel their circumstellar disks. From Meilland et al. (2011b).

Some Be stars show large variability that may be related to binarity. For instance, this is the case of two well studied objects : Achernar and δ Sco. Achernar is a quasi-cyclic Be star with a period of formation and dissipation of the equatorial disk of about 12 years. It was observed at a minimum of activity by Domiciano de Souza et al. (2003) and the authors found that the star was strongly flattened by close-to-critical rotation. Using these interferometric observations as well as spectroscopic follow-up of a full cycle of activity from Vinicius et al. (2006); Kanaan et al. (2008) managed to fully model the environment of this object which consists in a steady polar wind driven by radiative pressure and a transient equatorial disk which is produced during a brief outburst. The ejected matter then propagates into the CSE with an expansion velocity of the order of $0.2\,\mathrm{km}\cdot\mathrm{s}^{-1}$. The cause of the ejection remained mysterious until the discovery of a companion star using the VLT/NACO instrument (Kervella et al., 2008). New observations will soon be executed to constrain the companion orbit and determine whether or not it could be the cause of the cyclic variations of Achernar.

On the other hand, δ Sco is a well-known binary system. First evidence of its multiplicity was reported by Innes (1901) using the lunar occultation technique. However, this work was forgotten for a long time, and the binary nature of δ Sco was rediscovered with three different techniques in 1974: by speckle-interferometry (Labeyrie et al., 1974), lunar occultation (Dunham, 1974), and intensity interferometry (Hanbury Brown et al., 1974). The extremely eccentric orbit (e$\simeq$0.94) was then constrained by many authors using speckle and long-baseline interferometry (Bedding, 1993; Hartkopf et al., 1996; Miroshnichenko et al., 2001; Tango et al., 2009; Tycner et al., 2011). However, the δ Sco system did not show clear evidence of the Be phenomenon until its June 2000 periastron. At this epoch, Otero et al. (2001) found a 0.4 mag brightening of the object. Simultaneous spectroscopic observations published in Fabregat et al. (2000) showed evidences of strong Hα emission lines. Using spectroscopic measurements obtained at different epochs and assuming that the matter was concentrated in a Keplerian rotating disk, Miroshnichenko et al. (2003) suggested that the ejected matter was expanding at about $0.4\,\mathrm{km}\cdot\mathrm{s}^{-1}$, a velocity compatible with the one found for Achernar. Thanks to new spectrally-resolved VLTI/AMBER and CHARA/VEGA observations, Meilland et al. (2011a) managed to probe the CSE structure and confirmed Miroshnichenko hypothesis that the ejected matter is concentrated in a Keplerian rotating disk. They also constrained the stellar rotational velocity and found that this star was likely to rotate far below its critical limit, at about 0.7V$_c$. Finally, they detect asymmetries in their data that can hardly be modeled under Okazaki (1997) one-armed oscillation framework, and that could be due to a tidal warping of the disk by the companion periastron passage (see Fig.3), as is described in Moreno et al. (2011).

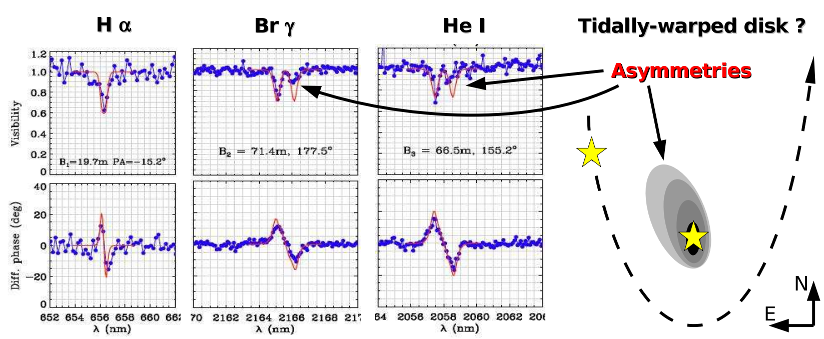

Fig. 3 Illustration of the δ Sco system close to the periastron passage. The three left figures are from Meilland et al. (2011a), showing the AMBER data (blue) together with a kinematic model of a rotating disk (red). Meilland et al. (2011a) proposed that the differences between the model and the data (arrows) could be the signature of a tidally-warped disk around the primary star (right sketch).

In the case of these two stars, the binarity clearly play a important role in the mass-ejection process. However, whether the companion action is direct, i.e. by canceling the residual stellar gravity at the surface of the central star, or indirect, i.e. by impacting on other physical processes such as non-radial pulsations, remains an open question. Moreover, the influence of binarity on the Be phenomenon is not limited to the mass-ejection, it can also affect the reorganization of the gas in the CSE.

3 Interactions in the most massive stars

As seen in the previous section, disks encountered around Be stars are more and more found to be rotating close to Keplerian velocities. This applies also to some B[e] candidate supergiant stars.

The situation for Be stars is somewhat complicated, as several hypotheses exist to explain the disk formation and steadiness. For B[e] stars, which are surrounded by dense disks of plasma *and* dust, the situation is even more complex. The dust survives much closer to these hot star than expected so far (Meilland et al., 2010; Millour et al., 2009; Domiciano de Souza et al., 2007), meaning that complex radiative transfer processes such as line-blanketing could occur in the gas disk of these stars. The B[e] supergiant stars critical rotation rate is strongly decreased by the increase of their radius while leaving the main sequence. Therefore, rotation alone is certainly not sufficient to explain the creation of a circumstellar disk without invoking the influence of a close companion (Miroshnichenko, 2007).

Such influence seems clear in the few cases where companion stars were detected, like in the binary system HD 87643 (Millour et al., 2009, see Fig. 4). In this B[e] system, enshrouded inside a complex nebula reminiscent of the ones found around LBVs, the presence of the companion provides a key to understand the whole range of features observed in the system, if it has an eccentric orbit:

- the extended nebula, that could come from a past outburst of the system at one periastron passage,
- the series of arc-like structures found in the same nebula, tracing more recent periastron passages
- the main star disk, formed by the direct interaction with the companion star

The supergiant A[e] star HD 62623 is also informative in this context (Millour et al., 2011; Meilland et al., 2010). It is an A supergiant showing the “B[e] phenomenon”, namely a spectrum dominated by strong emission lines (allowed and forbidden), and a large infrared excess. Spectrally and spatially resolved AMBER/VLTI observations in the Brγ line have shown that the supergiant star lies in a cavity, and is surrounded by a rotating disk of plasma. The Brγ line at the location of the central star is *in absorption* showing that it is a normal A-type star, albeit with a significantly large v*sini* of about $50\,\mathrm{km}\cdot\mathrm{s}^{-1}$. By contrast, the Balmer and Bracket lines are wider (*vsini* of about $120\,\mathrm{km}\cdot\mathrm{s}^{-1}$), and the AMBER observations demonstrated

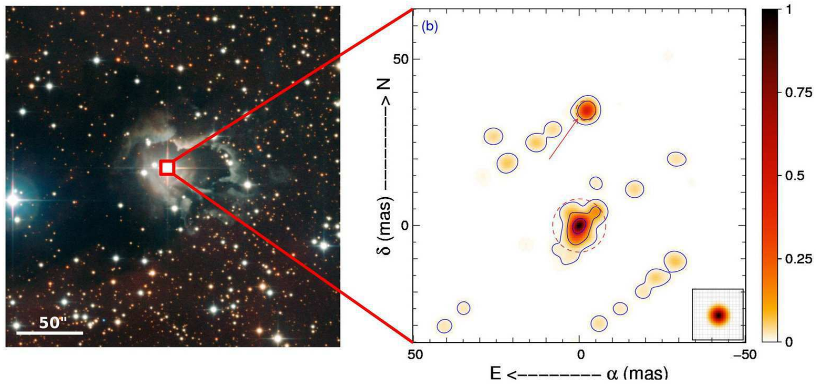

Fig. 4 Images of HD87643 at two highly (1:1000) different scales. Left is the large-scale nebula, exhibiting its complex shape and its inner arc-like structures, right is the interferometric small-scale image, showing the companion star (arrow) and the circumstellar disk (dotted circle). Figures from Millour et al. (2009).

that they originate from a disk of plasma, most probably in Keplerian rotation (See Fig. 5). In absence of any proof of binarity, it is often difficult to understand how such a dense equatorial disk could have been generated. However, HD62623 is a known binary with a stellar companion that orbits close to the supergiant with a period of about 136 days (Plets et al., 1995). The mass ratio inferred is very large, and the companion is probably a solar-mass star, hence unseen in the AMBER images. Plets et al. (1995) proposed that an efficient angular momentum transfer occurs near the L2 Lagrangian point of the system, propelling the mass lost from the supergiant by its radiative wind and probably also by strong tides into a stable dense circumbinary disk.

Similarly, the evolved system υ Sgr was recently investigated-again using spectroscopy and optical interferometry in the near-IR and the visible (Bonneau et al., 2011; Netolický et al., 2009; Koubský et al., 2006), evidencing a dense circumbinary disk, apparently long-lived.

4 Novas, bipolar nebulae, and the underlying binary system

Novas are formed of a white dwarf (WD) and a red giant star, whose material is accreted on the WD surface. When enough material is accreted, thermonuclear reactions can light up, expelling a fireball, which we directly observe, usually using spectroscopy, or imaging a few years after. Novas are suspected to be the progenitors of type I supernovas, as the accreted material piles-up, nova after nova, providing the good conditions for core-collapse.

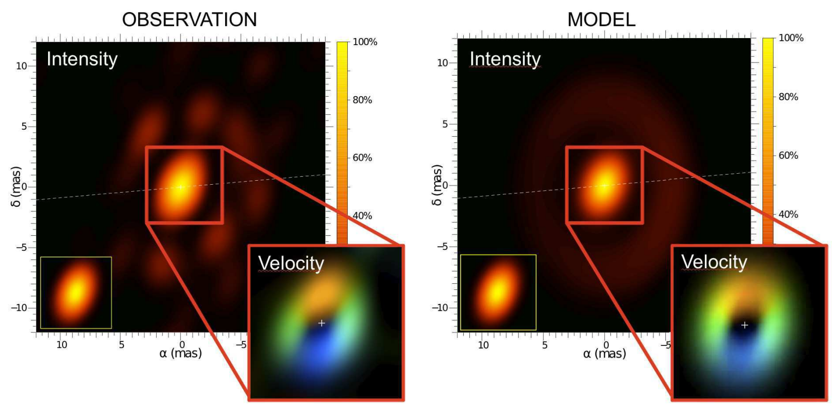

Fig. 5 The VLTI observations of the A[e] system HD62623 (here, the figure of the press release) showed that the dense circumbinary disk (Meilland et al., 2010, outer red ring in both the image – left – and the model – right) seems constantly fed by an inner plasma disk (central yellow dot), probably in Keplerian rotation (insets), whose angular momentum originates from a solar mass companion (Millour et al., 2011).

Such fireballs are seen as bipolar nebulae years after the explosion, but an open question remained to know if that was an intrinsic shape of the explosion or if it was shaped after, by the CSE.

A new field of research was open by the first spectro-interferometric observations of a nova in Chesneau et al. (2007). This letter evidenced an elongation of the nova fireball, just a gasp after the outburst (5.5 days). This first clue of bipolarity for one nova could not be repeatedly achieved when observing a second nova with the VLTI (Chesneau et al., 2008), due to a different observing configuration. Nevertheless, more recently, Chesneau et al. (2011) provided firm evidence of bipolarity on a third nova, observed in 2011.

The presence of bipolar nebulae at the very first moments of outbursts in massive stars (e.g. LBVs like η Car) or less massive systems (e.g. planetary nebulae, novas) is still a broad and controversial subject. Indeed, bipolarity in the nebula is very often associated with binarity in the core (de Marco, 2009). But the inverse is not true, namely that binarity will essentially imply at a moment of the life of the system a bipolar ejection of material.

The key question is therefore to link the initial parameters of the system to:

- its evolution,
- the formation of a circumstellar disk (such as the ones encountered around B[e] stars or interacting systems such as υ Sgr, or δ Sco),
- the occurrence of outburst events, forming rapidly a dense bipolar nebula.

but it still has to be answered.

5 Discussion, concluding remarks

With this paper, we tried to link the presence of a companion star to the presence of CSEs, by providing recent examples of high-angular resolution observations.

interferometry has brought the view of highly structured CSEs around several massive stars, in the form of thin or thick disks, plus sometimes the presence of a companion star. The formation scenario of these CSEs remains to be determined, but the ingredients seem to count, among others, a binary system, including a hot, massive star, a dense disk, and perhaps also a fast-rotating star.

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